

Neutrino Mass² Inferred from the Cosmic Ray Spectrum and Tritium Beta Decay

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An earlier prediction of a cosmic ray neutron line right at the energy of the knee of the cosmic ray spectrum was based on the speculation that the electron neutrino is a tachyon whose mass is reciprocally related to the energy of the knee, E_k . Given the large uncertainty in E_k , the values of m_ν^2 corresponding to it are consistent with values recently reported in tritium beta decay experiments.

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INTRODUCTION

In this article we note that recent data on the position of the knee of the cosmic ray spectrum, [1] interpreted in the context of a “tachyonic” ($m_{\nu_e}^2 < 0$) electron neutrino model, [2,3] yields a value for $m_{\nu_e}^2$ that is consistent with results from recent tritium beta decay measurements. [4–6] Moreover, the tritium experiments may offer greater support for the hypothesis of a tachyonic neutrino than some observers realize.

Tachyons are hypothetical particles, first proposed in 1962, [7] which always travel at faster-than-light speed, $v > c$, yet are consistent with all the equations of special relativity. Tachyons need to have an imaginary rest mass, m , or $m^2 < 0$, in order to have a real observable momentum, $p = \gamma mv$, and energy $E = \gamma mc^2$ [8]. Faster-than-light tachyons should not be confused with recent reports of observations of superluminal electromagnetic wave propagation. [9] The phenomena described in those reports are consistent with Maxwell’s equations, do not allow superluminal information or energy transmission, and do not involve any new particle whose rest mass is imaginary.

Of all the known particles there is one category – the neutrinos – whose measured masses are sufficiently close to zero, given the experimental uncertainties, that we cannot rule out the possibility of them being tachyons with $m^2 < 0$. In fact, over the years most experiments looking at the endpoint of the beta decay spectrum have yielded negative results for $m_{\nu_e}^2$. For that reason Chodos et al. suggested in 1985 that neutrinos are tachyons. [10] One of the strange properties of tachyons is that the sign of their energy gets reversed when they are observed from the standpoint of an observer travelling with sufficiently high – but sub-light – speed. As a result, an emitted tachyon in one reference frame can become an absorbed tachyon in another. Consequently, Chodos et

al. proposed in 1992 that if the electron neutrino were a tachyon then protons should be able to beta decay if their energy exceeded some critical value that depends on the neutrino mass. [11] Above that threshold energy, an emitted positive energy antineutrino in the lab reference frame could be interpreted as an absorbed negative energy neutrino (from some background sea) in the proton rest frame. In other words, the rest frame observer reinterprets the proton decay process: $p \rightarrow n + e^+ + \nu$ as an antineutrino *absorption*: $\bar{\nu} + p \rightarrow n + e^+$ [12]

In 1993 Kostelecky suggested that a curious feature of the cosmic ray spectrum known as the “knee” or abrupt change in power law that occurs around 4.5×10^{15} eV (or 4.5 PeV) could be explained on the basis that the electron neutrino is a tachyon. [13] The idea was that if the cosmic ray spectrum obeyed a single power law for all energies above 1 GeV, then protons would be increasingly depleted from the spectrum above their decay threshold, resulting in the knee of the spectrum.

A COSMIC RAY NEUTRON LINE?

In 1999, following Kostelecky’s conjecture, Ehrlich fit a number of features of the cosmic ray spectrum under the speculative tachyon neutrino hypothesis. [2] Ehrlich’s model predicted a neutron line in the cosmic ray spectrum occurring at an energy where the knee of the spectrum occurs, cited as 4.5 ± 2.2 PeV. The reason why a neutron line was predicted is that when protons decay at energies above the threshold they give rise to a decay chain: $p \rightarrow n \rightarrow p \rightarrow n \rightarrow p \dots$ that stops just above threshold, hence resulting in a neutron “pile-up” just above the knee of the spectrum.

One distinguishing characteristic of neutrons in the cosmic rays is that being neutral they should point back to their sources unlike charged protons that are deflected by magnetic fields and approach Earth from “random” directions. Hence, as long as the nucleons in the hypothetical decay chain spent most of their time en route to Earth as neutrons, [14] they should point back *approximately* [15] to their source, and survive a trip for source distances that would normally rule out the possibility of sub-EeV neutrons in the cosmic rays, given their 10 minute lifetime, and likely source distances. In a second 1999 article, Ehrlich showed that an experiment from 1983 [16] actually gave some support for a 4.5 PeV neutron line from the source Cygnus X-3, at a 5σ level, although the original authors made no such claim. [3]

However, this support for the hypothesized neutron

line was based on a single source in a single experiment. [17] The hypothesized neutron line would need to be observed from many sources in an all-sky survey in order to gain credibility. The idea is to see if cosmic ray events falling in a narrow energy window centered on the knee (within the energy resolution of the experiment) tend to cluster about specific points in the sky (the sources). Note, however, that the location of the knee is highly experiment-dependent, given the absence of any other feature in the cosmic ray spectrum that could define the energy scale, and permit an accurate energy calibration. Thus, wherever the knee appears in a particular experiment, whether at 4.5 PeV or some other value, one should search for the predicted neutron line by looking for spatial clustering of cosmic ray events in a narrow energy window centered on the position of the knee.

One recent very high statistics experiment shows the knee to occur at 1 PeV. [1] In the tachyon neutrino hypothesis simple kinematics shows that the position of the knee is inversely related to the absolute value of the rest mass $|m| \equiv \sqrt{-m^2}$ of the neutrino, i.e., $E_{knee} = 1.7/|m|$ PeV. [2] Hence a knee occurring at 1 PeV rather than 4.5 PeV corresponds to $m^2 \approx -3\text{eV}^2/c^4$ rather than $-0.14\text{eV}^2/c^4$ as earlier suggested in ref. [2] This change should make the neutrino mass prediction of much greater interest to groups measuring m_ν by looking at the tritium beta decay spectrum.

TRITIUM BETA DECAY EXPERIMENTS

We do not argue that 1 PeV is necessarily a better value for the position of the knee than 4.5 PeV, but only that: (1) there is some evidence it may be – since the implied 4.5-fold reduction in the energy scale could then explain the arrival of cosmic rays supposedly above the GZK cutoff without requiring any new physics, [18,19] and (2) wherever the true position of the knee, it is known so poorly that some values yield neutrino masses that could be observed in the current generation of tritium beta decay experiments. Two recent measurements of the electron neutrino mass² are by the Troitsk group: $m^2 = -1.9 \pm 3.4_{stat} \pm 2.2_{sys}\text{eV}^2/c^4$ [4] and the Mainz group: $m^2 = -1.8 \pm 5.1_{stat} \pm 2.0_{sys}\text{eV}^2/c^4$ [5,6].

Let us consider two interpretations of this pair of experiments – the first being to accept the results at face value. In that case, one can only meaningfully give an upper limit to m^2 , given the size of the statistical and systematic errors. The results would be consistent with a $m^2 \approx -3\text{eV}^2/c^4$ neutrino, but without offering the hypothesis any real support. Under a second interpretation we find that the Troitsk and Mainz experiments might actually offer much stronger evidence for a tachyonic neutrino mass than is implied by the preceding values cited for the neutrino mass². Troitsk sees an anomaly (a bump) in their beta spectrum near the upper endpoint – a feature that is consistent with an electron neu-

trino of mass $m^2 \approx -10$ to $-20\text{eV}^2/c^4$ according to that group [4]. This bump is dealt with by simply removing it (through an ad hoc fit), and then using the residual data to find a value for the neutrino mass cited in the previous paragraph, thereby “eliminating the negative value problem.” [4]. This procedure is justified by the interesting statement that: “negative values for m_ν ² obviously indicated that there exist some systematic effect not taken into account.” [4] The Mainz group also sees an indication of the same anomaly, but only in one of four data taking periods, [5]

How seriously should one take these “anomalies” seen to some extent in both experiments? The claim by Troitsk that their anomaly seems to show a periodic shift in position with time (not supported by Mainz) would seem to indicate that its origin is in fact possibly due to some artifact, rather than a genuine tachyonic neutrino. However, if the claimed periodicity of the anomaly cited by Troitsk is only a statistical fluctuation, one would need to consider more seriously the possibility of an electron neutrino with $m^2 \approx -10$ to $-20\text{eV}^2/c^4$. Moreover, if the bump is a real feature of the spectrum, one could explain its shift in width and position from run to run in the Troitsk experiment, and its nonappearance in most of the Mainz runs on the basis of a changing energy resolution during the course of each experiment, and better resolution in the Troitsk experiment. (Note that a tachyonic neutrino in that mass² range would require the true energy of the knee of the cosmic ray spectrum be in the range 0.4 to 0.5 PeV – a value which cannot be ruled out, given the large range in knee positions seen so far.)

Searches for a neutron line in the cosmic rays at the spectrum knee (wherever it occurs in a given experiment), and more accurate tritium beta decay experiments are needed to resolve the above issues. However, experimenters who analyze their data in the belief that “negative values for m_ν ² obviously indicated that there exist some systematic effect not taken into account” [4] will never be able to provide evidence for a genuine tachyonic neutrino – should it exist.

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- [14] In the absence of a field theory of tachyons, we do not know what the proton lifetime is as a function of the proton energy. However, it seems probable that for energies significantly above the proton decay threshold, the proton mean free path before decay will be much less than that for the neutron, because time dilation causes the neutron mean free path to increase with energy, while at the same time the phase space for the proton decay process (zero at threshold) increases rapidly with energy.
- [15] They cannot point back exactly to the source, since they do spend a fraction of their time en route as protons, which tends to randomize and systematically shift their direction – which blurs and shifts the image of any point source by an amount that would depend on its distance. According to one report summarizing ten years of observations on Cygnus X-3, events appear to be distributed around the source with a Gaussian point spread function which is four times wider than the experimental angular resolution. See, W.W.M. Allison et. al., 26th International Cosmic Ray Conference, Salt Lake City, 1999.
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